GLider Acoustics Sensing of Sediments (GLASS): experiments and data analysis

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GLider Acoustics Sensing of Sediments (GLASS): Experiments and data analysis

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James H. Miller

This document, which describes work performed under the Project GLASS – GLider Acoustics Sensing of Sediments of the STO-CMRE Programme of Work, has been approved by the Director.

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Executive Summary: Seabed reflectivity and scattering properties are critical parameters in sonar performance predictions for both Anti-Submarine Warfare and Mine Counter Measures. Databases exist containing some bottom information, but these data are often unreliable resulting in poor performance predictions. Complex experimental and data analysis schemes have been demonstrated to provide high-fidelity seabed properties. These systems are often time consuming and expensive to deploy, limited to local measurements and require significant human interactions. The advanced technological development of Autonomous Underwater Vehicles (AUVs) and gliders offers the opportunity to survey large areas of the ocean over long periods of time. This has in particular been demonstrated during exercises where the objective was to characterize the spatio-temporal water column properties. These types of underwater vehicles have recently been equipped with low power consumption multi-channel data acquisition systems and an array of hydrophones. This additional acoustic payload extents the capability to characterize the underwater environment by acquiring passive and active acoustic signals. Seabed characterization has in the past been demonstrated successfully by using natural-made ambient noise or noise sources of opportunity, such as distant shipping, received on long moored or drifting vertical arrays. The objective of the GLASS project is to investigate the feasibility to transition this ambient noise methodology to autonomous vehicles equipped with compact hydrophone arrays. In 2012 and 2013, CMRE conducted two experiments (GLASS'12 and GLASS'13, respectively) in different shallow-water areas deploying an underwater vehicle with a noise-mounted compact line and tetrahedral hydrophone array. The aim during the experiments was to acquire sea surface generated noise and distant shipping for seabed characterization. The experimental results with accompanying data analysis and numerical modeling are presented. Although the aperture of the compact arrays employed was short (and led to degraded resolution) they show sensitivity to the seabed properties, and potential for operational and on demand, efficient mapping of seabed properties in denied areas.

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GLider Acoustics Sensing of Sediments (GLASS): Experiments and data analysis

Peter L. Nielsen, Lanfranco Muzi, Martin Siderius, James H. Miller

Abstract:

Seabed characteristics (geoacoustic properties and scattering strength) are critical parameters for sonar performance predictions. However, this bottom information is considered very difficult and expensive to achieve in the scientific community. In this report, an efficient method for inferring the seabed properties is presented; it relies on a previous methodology using long moored or drifting hydrophone arrays. Results from the GLASS'12 and GLASS'13 sea trials demonstrate the feasibility of using the technique by deploying a hybrid autonomous underwater vehicle hosting a unique hydrophone array consisting of a five-element vertical line array and a four-element tetrahedral array. Seabed reflection and layering properties are estimated from sea surface generated ambient noise acquired during the two trials in different shallow-water areas. Results from numerical modeling, data analysis and experimental measurements are presented with emphasis on comparing the seabed characterization at different locations with different bottom properties. Utilization of distant shipping was only demonstrated for the GLASS'12 trial data. The results obtained from both experiments demonstrate the potential of using autonomous underwater vehicles for seabed characterization and surface vessel tracking.

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Introduction

The properties of the seabed are critical parameters for reliable sonar performance predictions and for determining optimal sonar settings in a particular operational environment. However, the bottom properties are very difficult to obtain and are often required *a priori* and *in situ* for performance predictions and mission planning purposes. Traditionally complex equipment and strong human interaction from surface vessels are necessary for direct sampling (probes and acoustical remote sensing) of the seabed to provide estimates of the geoacoustic properties. This methodology is cost ineffective, computationally intensive, time consuming, and likely to be limited to local measurements outside denied areas. Databases exist containing seabed information, but the quality of these data are unknown and generally considered unreliable.

Autonomous Underwater Vehicle (AUV) and glider technologies provide an efficient platform for operations below the sea surface. These platforms, combined with low-power consumption data acquisition and sensor systems offer long duration and can cover large areas sampling the underwater environment covertly in denied areas. This has recently been demonstrated theoretically and during an exercise comprising several autonomous vehicles adaptively sampling the water column properties (conductivity, temperature and depth) [1,2]. A similar approach may be applied to map the seabed properties by mounting compact hydrophone arrays accompanied with a data acquisition payload on these vehicles. The acoustic signals carrying information about the seabed properties originate from sources of opportunity such as distant shipping and sea surface generated noise. Seabed characteristics have previously been determined successfully with sources of opportunity using long moored and drifting hydrophone arrays [3–8].

The Centre for Maritime Research and Experimentation (CMRE) initiated a project entitled "Seafloor Characterization using Gliders" in 2012 with the major objective to equip one of the CMRE AUVs/gliders, in this project the eFOLAGA, with a compact hydrophone array for seabed characterization using noise sources of opportunity. The research effort was financially supported by ONR-G (GRANT No. N62909-12-1-7040 and identified internally as project USA000113) and fund-matched by Allied Command Transformation under project ACT000207 in 2013. The project ran over two years with termination in 2013.

Two experiments were planned, with GLASS'12 (acronym for GLider Acoustics Sensing of Sediments 2012) experiment [9] conducted locally in the Mediterranean Sea in 2012, and the GLASS'13 experiment performed in conjunction with the ONR sponsored Target and Reverberation EXperiment (TREX) in the Gulf of Mexico off the coast of Panama City in 2013 [10].

The main objective of GLASS'12 was to demonstrate the feasibility of using a compact array of hydrophones and ambient noise for seabed characterization under controlled con-

ditions. Therefore, the eFOLAGA was mainly kept at fixed depth mounted on a bottom-moored frame, although an opportunity became available to perform measurements while the AUV was gliding through the water. The array, electronics and self-noise were concluded to perform extremely well during GLASS'12. One shortfall was the buoyancy adjustment of the AUV, which is necessary to stay at fixed depth while acquiring the ambient noise. Most of the data from GLASS'12 has been analyzed, and conclusions, recommendations, description of the equipment and experiments are provided in [9].

The vehicle buoyancy shortfall was addressed during the preparation for the GLASS'13 experiment by developing a closed-loop-feedback algorithm for the buoyancy system which provides a fixed-depth capability of the AUV. One of the objectives during the GLASS'13 experiment was to measure reflection loss and sub-bottom profiling over a large area by employing a stop-and-go sequence of the AUV. The eFOLAGA vehicle and hydrophone array were the same as used in GLASS'12 [9]. However, initial measurements of the system performance were conducted by bottom-mooring the AUV as during the GLASS'12 experiment. The quality of array and acquisition system was assessed to be of the high quality level as during GLASS'12. A total of approximately 45 minutes of ambient noise data was identified as usable for seabed characterization during the GLASS'13. Of this total, 40 minutes of the data were acquired while the AUV was bottom moored (moorings over a two day period), and only a few minutes of useful data while the vehicle was kept at constant depth and gliding through the water. The reminder of the data collected is contaminated by vehicle noise, most likely from self-induced activation of electronic control units.

In this report, comparisons between experimental results from the GLASS'12 and GLASS'13, and supporting numerical analysis are performed. The description of equipment and the GLASS'12 experiment is provided in [9] and will not be repeated except where necessary. The GLASS'13 was conducted as a TREX post-trial activity to minimize any interference from surface vessels and other acoustic equipment as it relies on measuring ambient noise. The clearance area was as defined during the TREX experiment and shown as the red box in Fig. 1. The eFOLAGA was deployed in the yellow confined area in Fig. 1, which is about 4.5 km from the coast and at the beginning of the TREX main reverberation track running parallel to the coast line [10]. The GLASS'13 preparation leveraged significantly from the TREX activities. In particular, high-resolution (1 m) multi-beam bathymetry mapping (Fig. 2, data made available by Dr Christian de Moustier and Barbara Kraft by the link in [10]) indicated variations of the water depth along the main reverberation track (red line in Fig. 2). This bathymetry variation correlates with acoustic backscatter intensity using the same multi-beam system. At shallower water depth the acoustic backscatter is high, and at deeper depth the backscattering is low. This is interpreted as a series of sand dunes (shallower areas) with mud-like patches (deeper areas) along the main reverberation track. Transition zones were identified (coordinates provided by Dr DJ Tang [10]) as TRANS01-TRANS03 in Fig. 2 with supporting core and diving activities at locations indicated by Mud01, Sand01 etc., and a combinations of these (Fig. 2). The eFOLAGA was deployed close to position VLA3 in Fig. 2 during the GLASS'13 experiment.
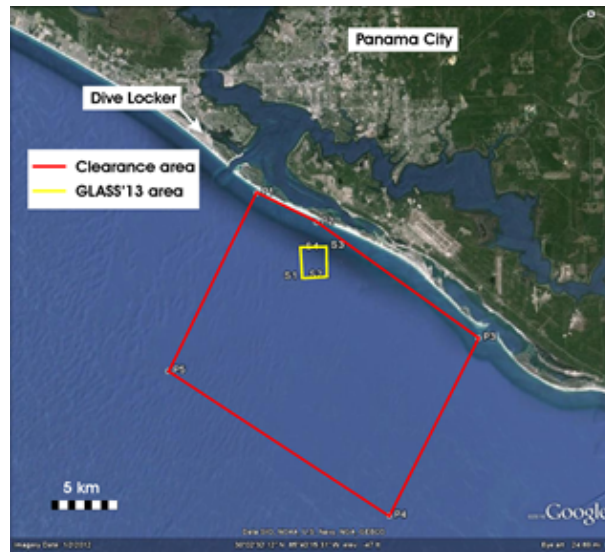
Figure 1: Clearance area (red box) defined for the TREX experiment in the Gulf of Mexico off the coast of Panama City, Florida, USA. The yellow box indicates the operational area during the GLASS'13.
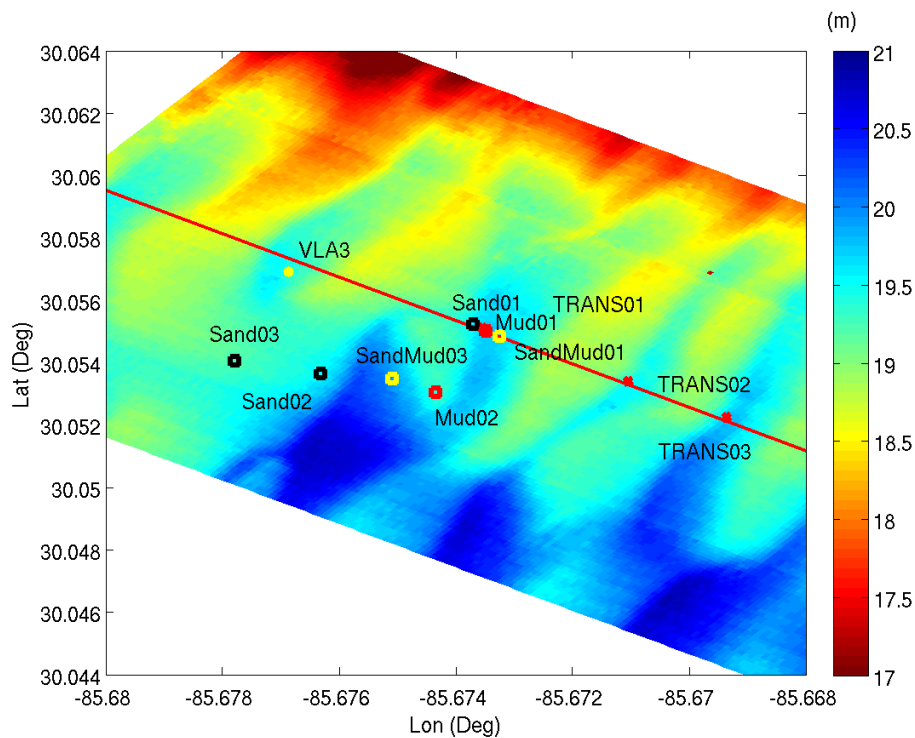
Figure 2: Bathymetry along the TREX main reverberation track (red line) obtained by a calibrated multi-beam system survey during the TREX experiment [10]. The undulations in the bathymetry along the main reverberation track have been shown to correlate with backscattering strength

2

Sensitivity analysis of array tilt and seabed properties

The test of the AUV control unit, array and acquisition system during GLASS'13 was performed while the vehicle was bottom moored as in GLASS'12. However, the AUV was tethered with rope and ballast during GLASS'13 in contrast to the specially manufactured rigid frame used during GLASS'12. The tethering of the vehicle may cause current and wave induced tilt of the compact vertical line array and, therefore, possibly degrade the performance of the seabed characterization. To conduct these tests, two deployment sequences were employed during GLASS'13:

- The vehicle was bottom moored with only the acquisition system turned on to evaluate the state of the array and self-noise of the acquisition system, and

- Bottom mooring with both acquisition system and control unit powered including logging of vehicle pitch and roll.

The latter would indicate any motion of the vehicle induced by current and waves which would alter the array orientation. However, the propeller of the vehicle turned on a couple of minutes after the deployment in this mode and repeatedly contaminated the noise measurements and, therefore, changed the attitude of the vehicle. Prior to the propeller turning on, the attitude sensors indicated a roll of around $3°$ and pitch close to $8°$. Numerical modeling of the impact of vertical array tilt on seabed characterization was performed using OASES [11]. The input parameters to the model were chosen to emulate the experimental set-up during the GLASS'13. The result of changing the array tilt by $10°$ compared to vertical is shown in Fig. 3. The measured array tilt is not expected to have a strong impact on the derived reflection loss and sub-bottom profiling, and a similar result was confirmed for a variety of bottom types. However, changing the array tilt to the extreme of $40°$ induces an apparent increase of the critical angle and a lower loss at steeper grazing angles (results not shown).

The seabed properties in part of the GLASS'12 experimental area may be characterized as silt-sand based on previous experimental activities [12] and by core data acquired during the GLASS'12 experiment [9]. The GLASS'13 site has been visited several times in the past by the majority of the Principal Investigators of the TREX, and results from these previous experiments indicate that the seabed is composed mainly of sand with shell debris and clay/silt inclusions [10, 13–15]. Therefore, the hydrophone-equipped eFOLAGA has been deployed in two different shallow-water environments during the GLASS'12 (soft bottom) and GLASS'13 (hard bottom) experiments. The OASES noise model was applied to a series of synthetic test cases to predict the ambient noise derived reflection loss in various shallow-water environments. The seabed is modeled as an infinite fluid halfspace, i.e., the bottom reflection loss is frequency independent and no fringes will appear as a function of grazing angle and frequency. The ten different bottom types considered are defined as in Table I in [16] with the associated geoacoustic properties. The results using
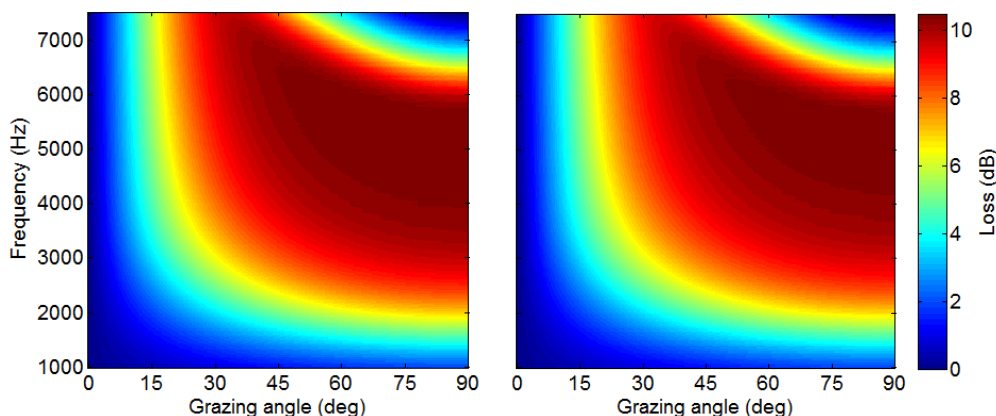
Figure 3: Reflection loss modeled for the vertical GLASS array (left panel) and with an array tilt of 10° (right panel).

the 0.4 m vertical array are shown in Fig. 4 for all bottom types ranging from clay to rock. Note the color scale changes after five bottom types.

In general the critical angle appears to increase from a soft (clay) to a harder (rock) bottom as one would expect. In addition, the lowest frequency at which this array provides sensible results also seems to increase as the bottom becomes harder. The latter phenomenon is at present not fully understood, but both the critical angle and the minimum usable frequency for the applied array configuration are expected to be strongly affected by the wide beam pattern of the array. Nevertheless, the ambient noise derived reflection loss is clearly affected by changes in bottom properties. This behavior of the measured ambient noise reflection loss indicates that these measurements alone may provide insight into the type of bottom being surveyed.

The same calculations were performed for a 32-element vertical array (total length 3.1 m), and the results are presented in Fig. 5. Clearly the length of the array and, therefore, the angular resolution has an impact on the ambient noise derived reflection loss. This reflection loss converges toward the plane wave reflection loss (Fig. 6) as the number of elements at the same hydrophone spacing increases, i.e., the length of the array increases. Although the noise derived reflection loss determined by a 5-element array does not represent the plane wave reflection loss, it clearly shows dependence on the bottom type. Meaningful seabed properties may therefore be obtained if the limitations of the short array ambient noise measurements can be compensated for or deconvolved.

Figure 4: Ambient noise derived reflection loss in dB for bottom types ranging from clay to rock using a 5-element vertical array and total length of 0.4 m.
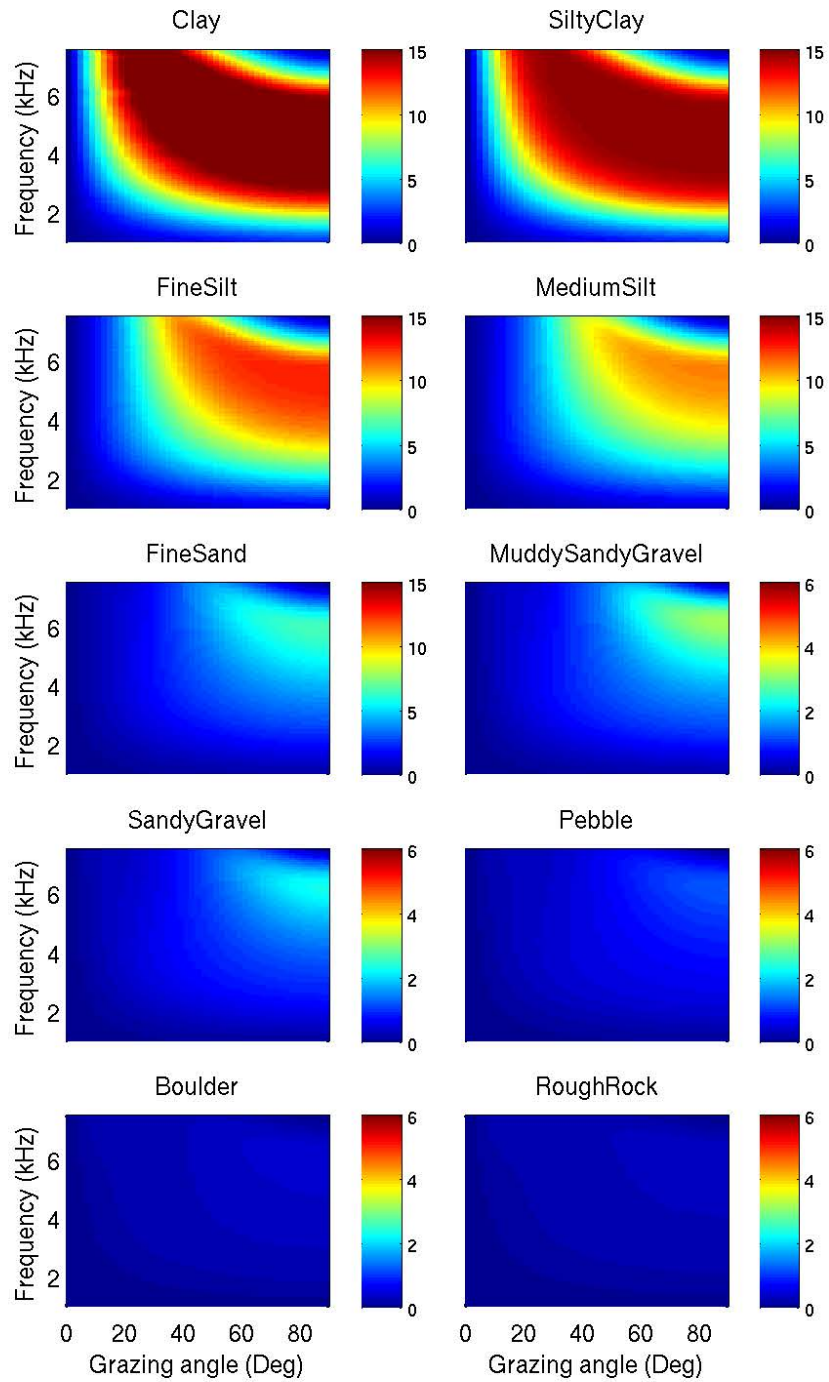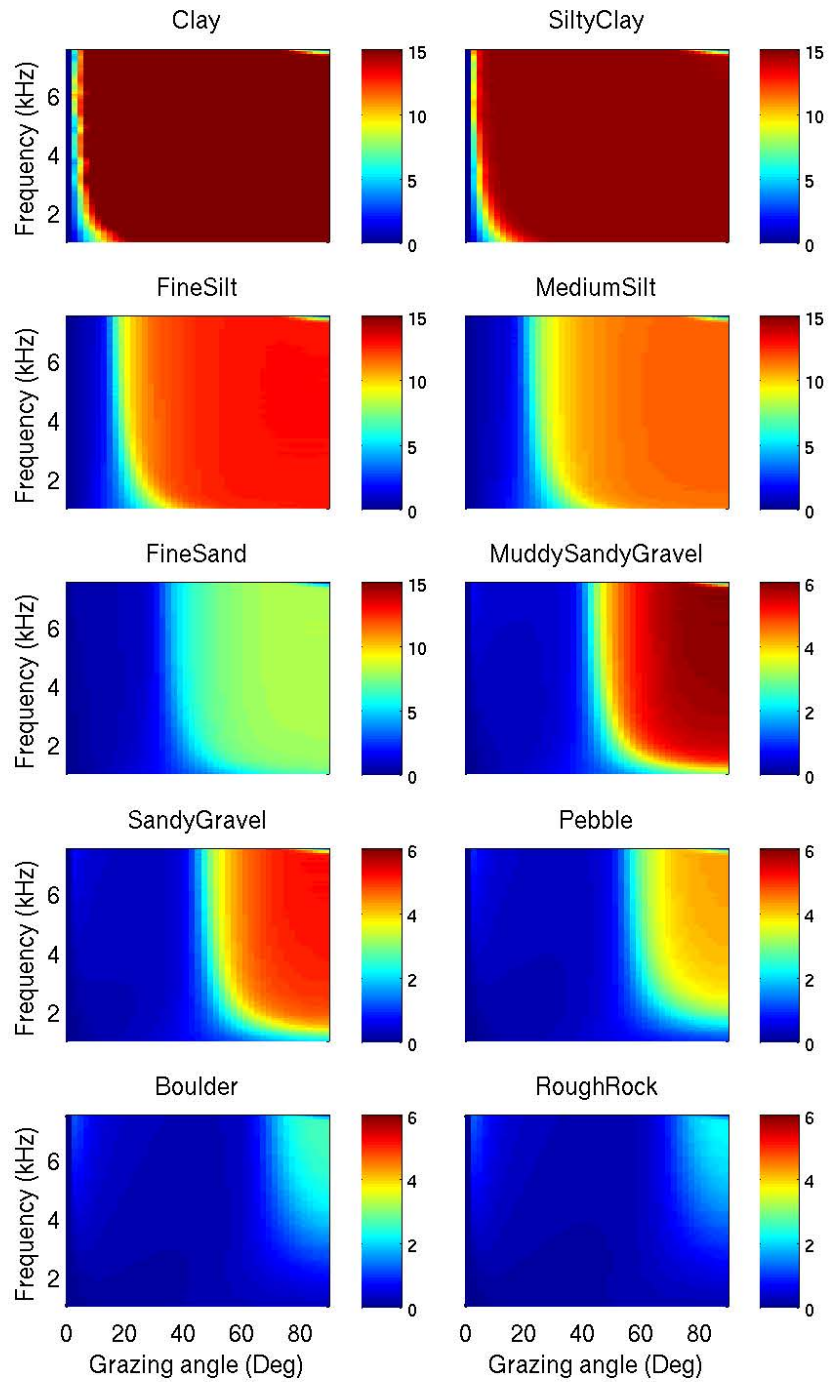
Figure 5: Ambient noise derived reflection loss in dB for bottom types ranging from clay to rock using a 32-element vertical array and total length of 3.1 m.
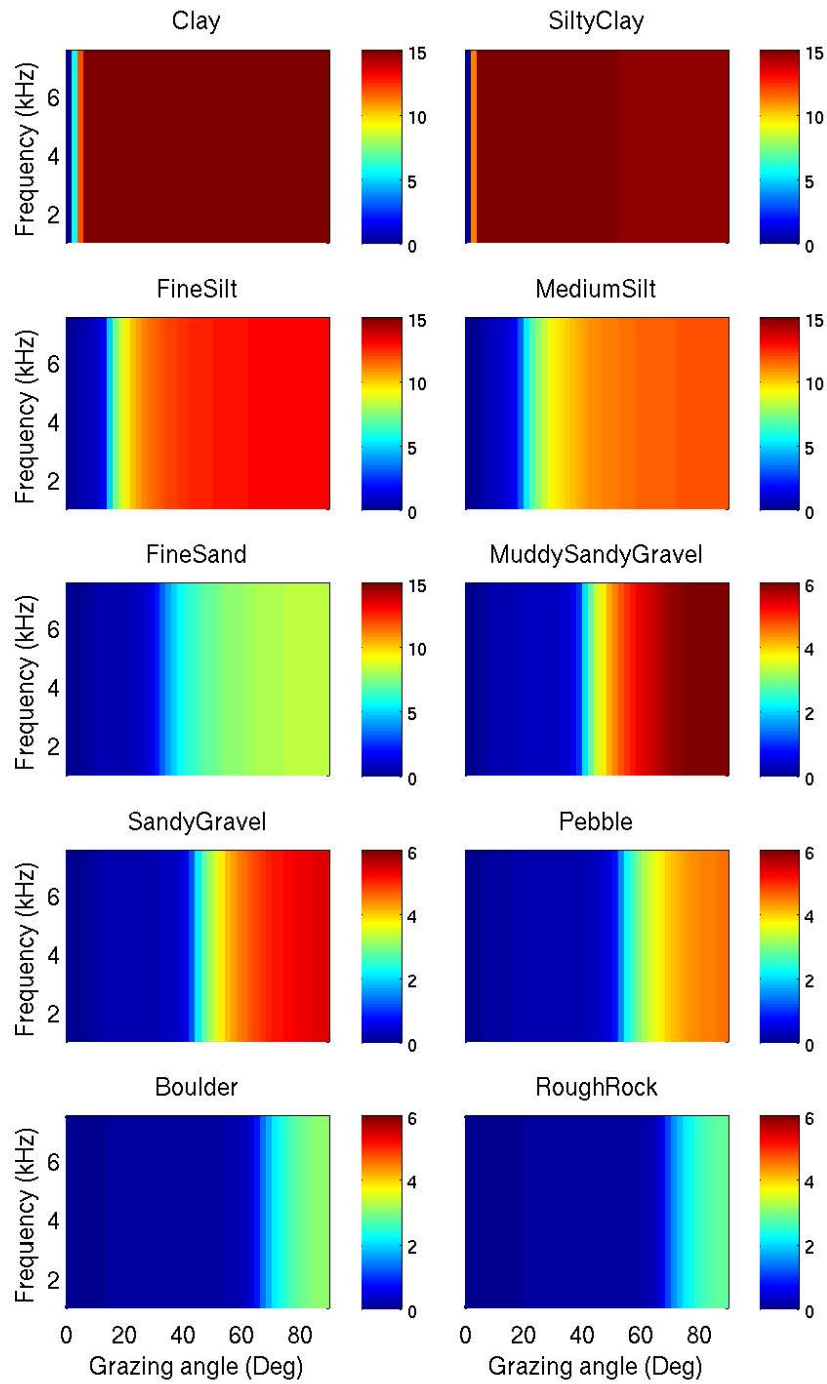
Figure 6: Plane wave reflection loss in dB for bottom types ranging from clay to rock.

3

Measured reflection loss and sub-bottom profiling

The ambient noise data acquired during the GLASS experiments are processed to a level that provides insight about the seabed properties. The processing consists of conventional plane wave beamforming of the vertical array data to provide seabed reflection loss in the frequency band from 1 to 7.5 kHz (array design frequency). The power ratio of the beamformer output between beams steered symmetrically down towards the seabed and up towards the sea surface defines the seabed reflection loss as a function of grazing angle and frequency. This technique is sensitive to loud interfering sounds such as shipping traffic as the conventional beamformer does not suppress these sound sources.

The sub-bottom profiling processing indicates stratification of the seabed. This is obtained by cross-correlating the downward endfire beam with the upward endfire beam of the vertical array and then transformation into time domain. In this case an adaptive beamformer is applied. It has better performance in suppressing loud interfering sounds and, therefore, increases the quality of the profiling.

Both beamformers require the cross-spectral density matrix of the ambient noise, and this matrix is constructed over a certain integration time. The integration time depends on the convergence of the seabed characterization, and may be affected by the level of ambient noise, acoustic frequency, seabed type and the array specifications (hydrophone spacing and array aperture). It was found that integration time of 70 s was sufficient in the examples presented in this report to represent the seabed reflection loss, while an integration time of only 30 s was applied for the sub-bottom profiling. The latter choice was mainly determined based on the presentation of the data, i.e., to utilize a sufficiently short integration time to present the profiling as a function of depth and measuring time (Coordinated Universal Time or UTC) and still preserve reflections off bottom layering if any.

Processed data from both GLASS'12 and GLASS'13 are compared to some extent to demonstrate the performance of the seabed characterization technique in different ambient noise fields and seabed types. All measurements during the GLASS experiments were conducted in water depths of around 20 m and moderate to low sea states. In general, the ambient noise level was 3-6 dB higher in the frequency band considered during GLASS'13 than GLASS'12 (Fig. 7). The spectral levels are obtained by averaging 50 time series of 3 s in duration. There are no pronounced spectral lines in the spectra that may contaminate the beamforming.

The conventional beam response of the same data presented in Fig. 7 vertical array data is shown in Fig. 8. The response is plotted on the same color scale with a dynamic range of 30 dB. In both cases higher sea surface noise levels (positive beam angles) are present compared to the bottom counterpart (negative beam angles), but the overall levels are higher for GLASS'13 data than the GLASS'12, consistent with the levels in Fig. 7. However, there is a relatively stronger horizontal component in GLASS'13 data which may be indicative of long distant noise sources (ships, oil rigs, land based activities, etc.).
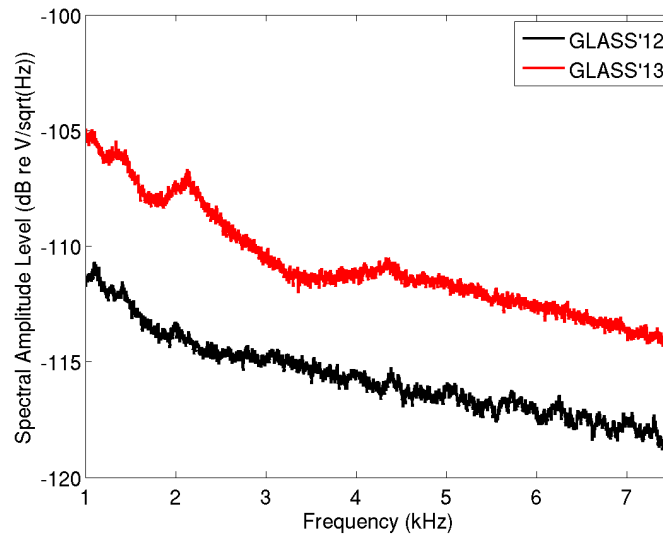
Figure 7: Typical spectral amplitude levels in the frequency band considered during the GLASS'12 and GLASS'13 experiments.

Examples of seabed reflection loss derived from the beam response are shown in Fig. 9. As the methodology would predict based on previous experimental activities in the same regions the appearance of the critical angle for the GLASS'12 site (18°) is lower than for the GLASS'13 (25°). In addition, it appears that the GLASS'13 reflection data have a higher minimum cut-off frequency than the GLASS'12 data. This may be introduced by the harder bottom in GLASS'13 following the explanation provided by the numerical modeling results (see Fig. 4). There are no interference fringes at higher grazing angles which either indicates that the bottom is composed of an infinite halfspace (frequency independent) or the angular resolution is too low to resolve the fringes.
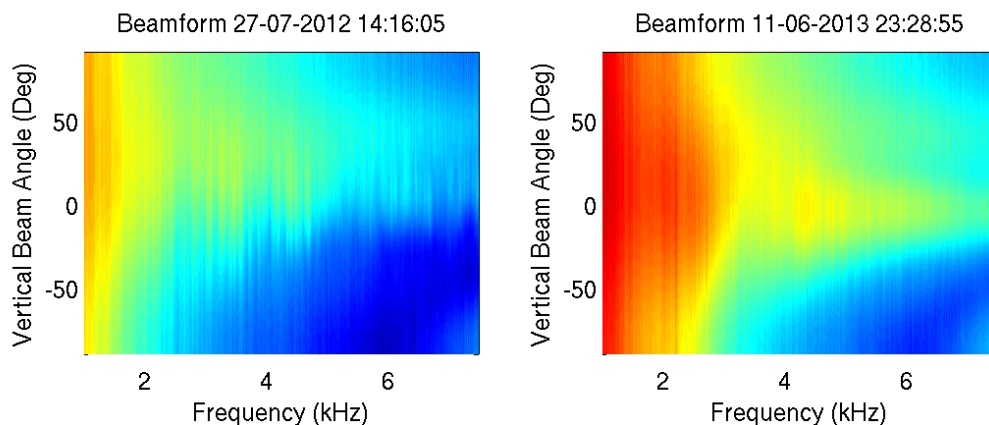

Figure 8: Conventional beamform response obtained during the GLASS'12 (left panel) and GLASS'13 (right panel).

The results in Fig. 9 were chosen out of a series of reflection loss curves acquired at each site showing sufficient sea surface generated ambient noise (Fig. 8) with minimum interfering distant sources, and expectations on how the reflection loss depends on grazing angle and frequency. It should be noted that not all experimental reflection loss curves behave like the those in Fig. 9.
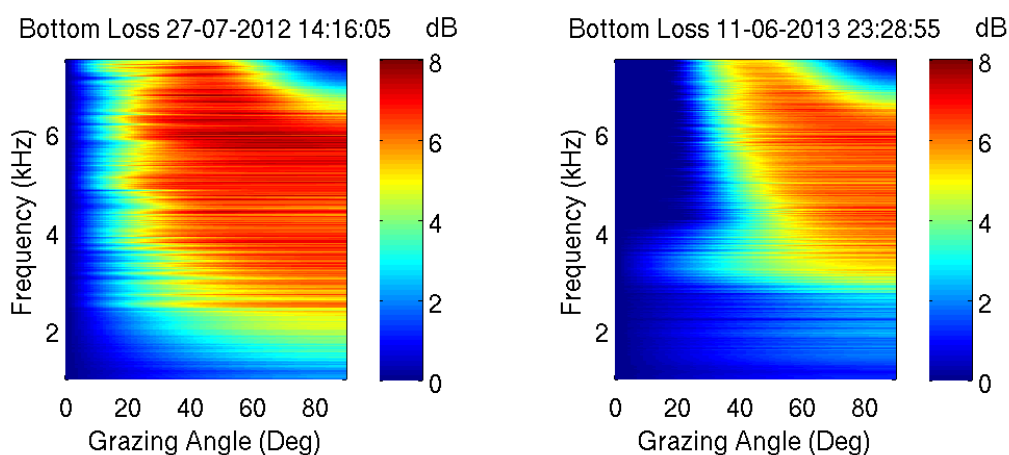

Figure 9: Ambient noise derived reflection loss from the two shallow-water experimental sites during GLASS'12 (left panel) and GLASS'13 (right panel).

As demonstrated in Figs. 4-6, the appearance of a frequency dependent critical angle (lower critical angle at higher frequencies) may be an artifact from the beamforming when the bottom is truly a halfspace. Other possible causes of this frequency dependent critical angle are unresolved gradients in the geoacoustic properties or layering, or sound speed dispersion. The latter is unlikely because the apparent decrease in critical angle as the frequency increases would contradict previous results showing dispersion effects in which sound speed (and hence critical angle) increases with frequency (not shown).

Sub-bottom profiling derived from ambient noise clearly showed a layer 3 m below the water-seabed interface at 18 m depth for site P in GLASS'12 (Fig. 10 upper panels) and a layer 4 m below the 22-m depth at site G in GLASS'12 (Fig. 10 middle panels) [9, 17]. This result was observed using both the tetrahedral and vertical array data (Fig. 10 left and right panels, respectively).

The sub-bottom profiling from the vertical array during GLASS'13 is shown in Fig. 10 (lower panel) when the eFOLAGA was bottom moored at a fixed location. Returns from the water-seabed interface at 20-m depth are clearly observed although the strength varies with measurement time (UTC). There is no indication of a layered bottom in the later arrivals. This agrees, to some extent, with chirp sonar data collected during the GulfEx'11 and GulfEx'12 experiments [10] (data not shown). The sub-bottom profile appears to be noisier for the GLASS'13 than the GLASS'12 data, and no profiling has yet been possible using the tetrahedral array for GLASS'13. The degradation could be caused by a loud interferer arriving at near horizontal as seen in Fig. 8 (right panel).
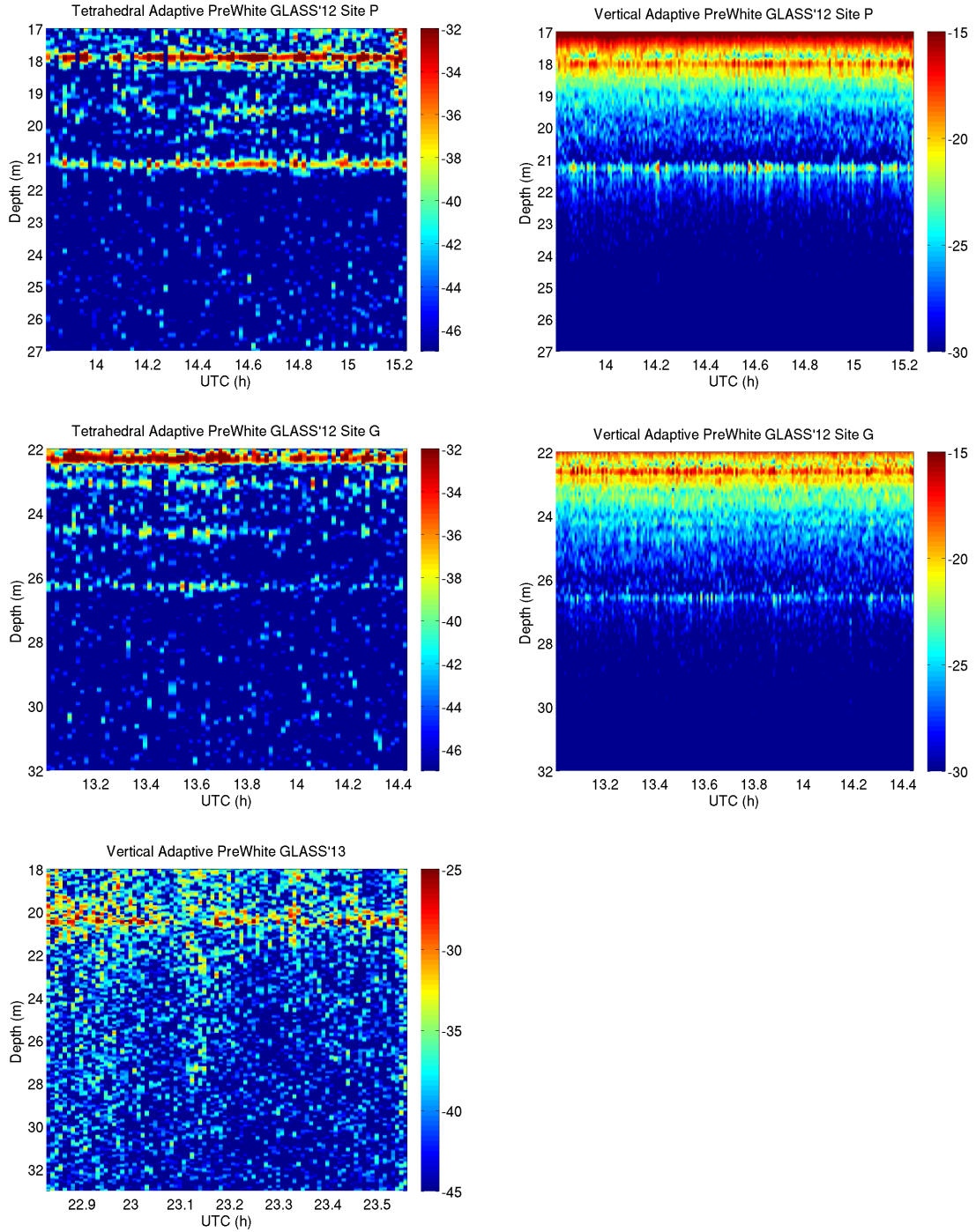
Figure 10: Sub-bottom profiling derived from ambient noise acquired on the tetrahedral array (left panels) and the vertical array (right panels) while the eFOLAGA was moored. The upper panels are measurements at site P and middle panels site G visited during the GLASS'12 experiment, and the lower panel is measurements during the GLASS'13 experiment. The color scales are in dB.

4

Estimates of geoacoustic seabed properties

Ideally the geoacoustic properties of the seabed could be inferred by the measured reflection loss to provide more flexibility in the application of the seabed characterization. This could be the case where the coherent transmission loss or full time series predictions have to be performed at a high fidelity level. These predictions require phase information of the reflection loss when the acoustic field interacts with the seabed. This phase information is not available in the direct measurements of the reflection loss from ambient noise presented here. Therefore, a sample of the derived reflection loss from the GLASS'12 and GLASS'13 sites has been used in a model-based inference method to estimate these geoacoustic properties.

The seabed is assumed to be an infinite halfspace with only three unknown parameters, namely density, attenuation and sound speed. The reflection loss derived from ambient noise is modeled by OASES [11], and the fitness of the modeling result to the experimental data is measured by a least-mean-square error function. The search for the set of seabed parameters that provides the best matched between model and data is performed exhaustively, i.e., values of density, attenuation and sound speed are changed one at a time. The parameter search space is discretized by 16 values for the attenuation covering the range from 0. to 1.6 dB/λ, 53 values for the sound speed in the range from 1460 to 2500 m/s, and 26 density values in the range from 1.0 to 3.5 kg/m^3. Grazing angles from 0 to 90° and frequencies from 1000 to 7500 Hz of the reflection loss were included in the search. Expectations are that the attenuation is the least sensitive parameter (mainly affecting the low grazing angles), the sound speed controls the appearance of the critical angle and the density is the dominant parameter at steeper grazing angles above the critical angle. An example of the ambiguity surface obtained by sweeping through the values of density and sound speed, while keeping the attenuation at the optimum value, is shown in Fig. 11. Clearly there is an optimum combination of the three geoacoustic parameters which provides the best match between model and data.

This inference of seabed properties has been obtained for both GLASS'12 and GLASS'13 data, and a comparison between modeled and measured reflection loss for optimum geoacoustic parameters is shown in Fig. 12. The optimum geoacoustic parameters determined by matching the model results to the data are given in Table 1 using 70 s duration samples from the two GLASS'12 sites (G and P [9]) and from the one site during the GLASS'13 experiment. None of the unknown seabed properties have optimum values at the search limits.
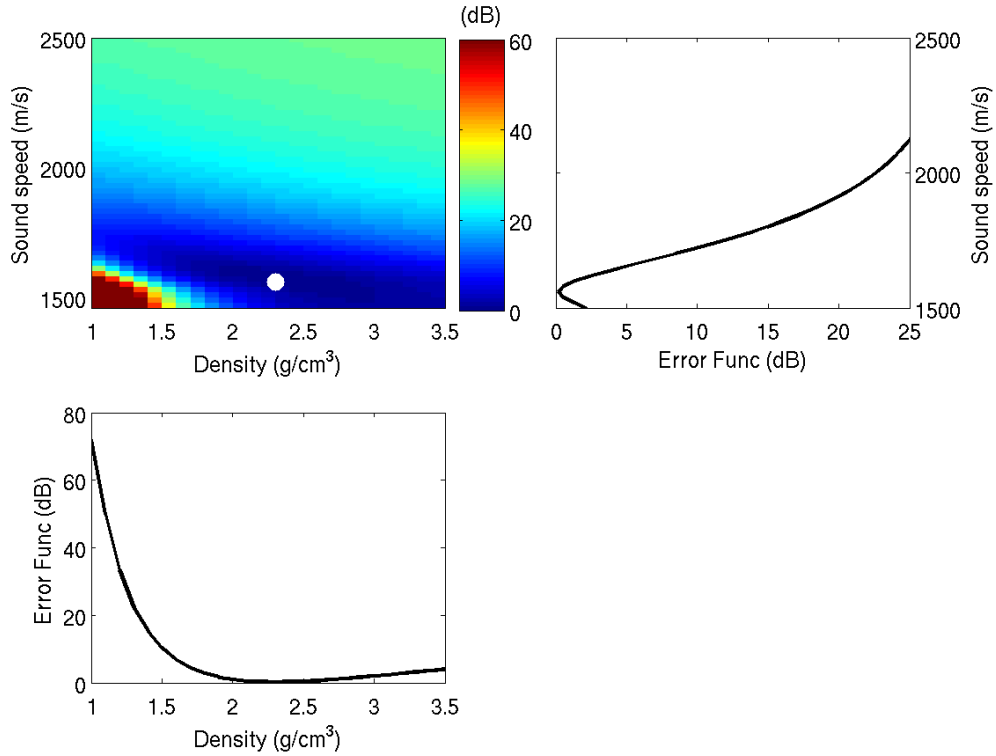
Figure 11: Ambiguity surface of the error function (cost or objective function) as a function of sediment sound speed and density as the geoacoustic parameters are swept one at a time. The attenuation is held at the optimum value of 0.7 dB/λ. Cross-sections pass through the white dot, with sound speed fixed (lower left) and with density fixed (upper right).

Table 1: Optimum seabed properties obtained by exhaustive sweep of sound speed, density and attenuation defined as the best match between ambient noise modeling and data as shown in Fig. 12.

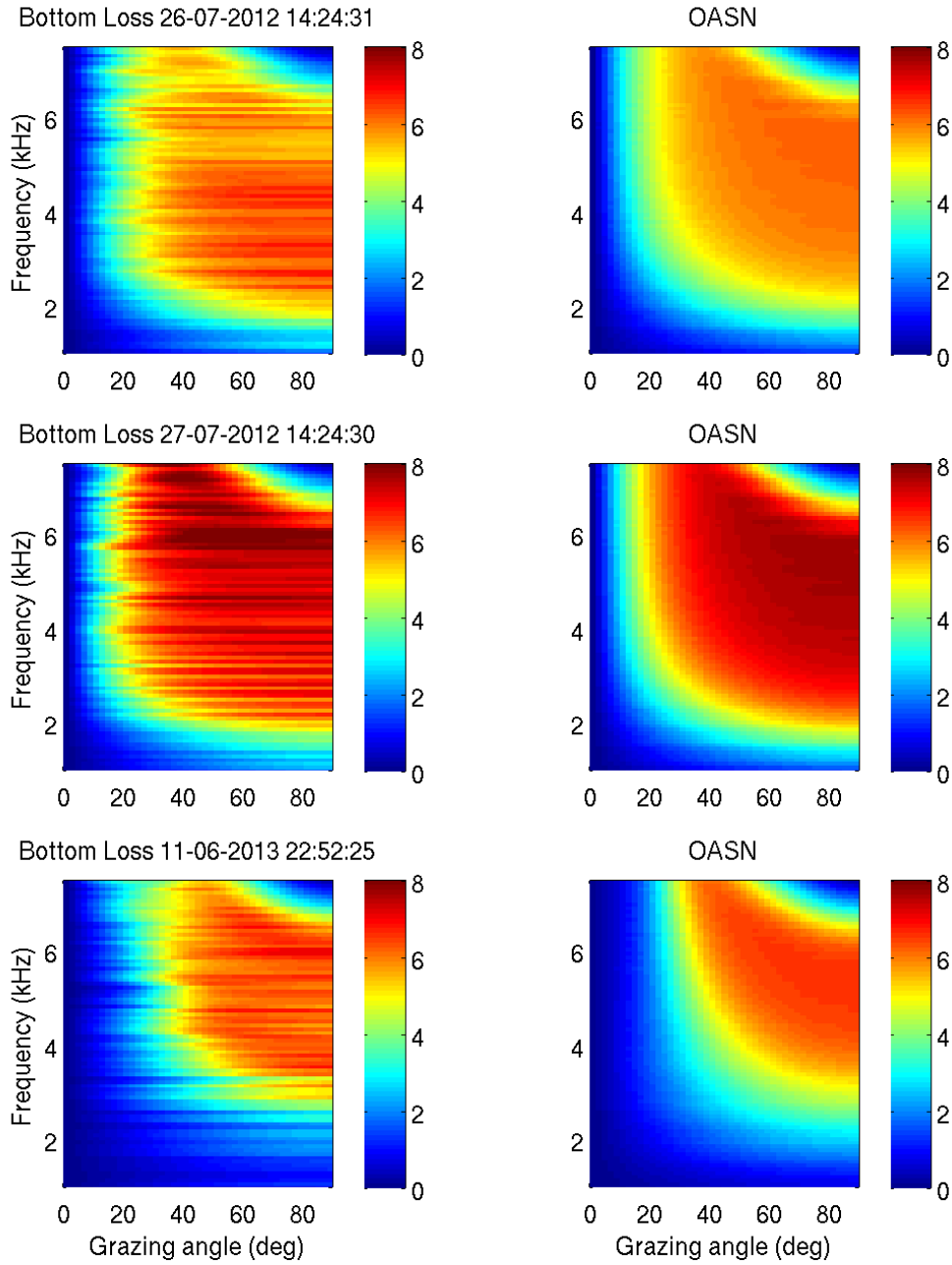|	Sound speed (m/s)	Density (g/cm^3)	Attenuation (dB/λ)
GLASS'12 site G	1560	2.8	0.70
GLASS'12 site P	1560	2.3	0.70
GLASS'13	1580	2.6	0.02

Figure 12: Model (right panels) and data (left panels) comparison of the reflection loss obtained during the GLASS'12 site G (upper panels) and site P (middle panels), and GLASS'13 (lower panels). The model results are achieved by using the combination of seabed sound speed, density and attenuation which provides the best match between model and data through an exhaustive search.

5
Synthetic extension of the GLASS array aperture

The reflection loss measured via ambient noise is negatively affected by the wide beams of the physical aperture, and the loss is therefore limited in resolution and apparently also in the usable frequency band (Fig. 4). Processing approaches suggest that the physical array aperture can be extended synthetically by utilizing the properties of the noise cross spectral density matrix as described in [17]. This technique has been applied to synthetic data produced by OASES simulating the GLASS'12 and GLASS'13 data. A comparison of reflection loss obtained using an array with double the physical aperture of that used in the GLASS experiments, with the reflection loss obtained by synthetically extending the GLASS array by two is shown in Fig. 13. The method introduces artifacts in its present formulation for such short arrays, most likely caused by the abrupt truncation of the across diagonal terms and zero padding of the cross-spectral density matrix. An example of the truncation and zero padding is illustrated in Fig. 14. Sophisticated methods to extrapolate the cross-spectral density matrix elements may exist and be used to improve this synthetic aperture extension.
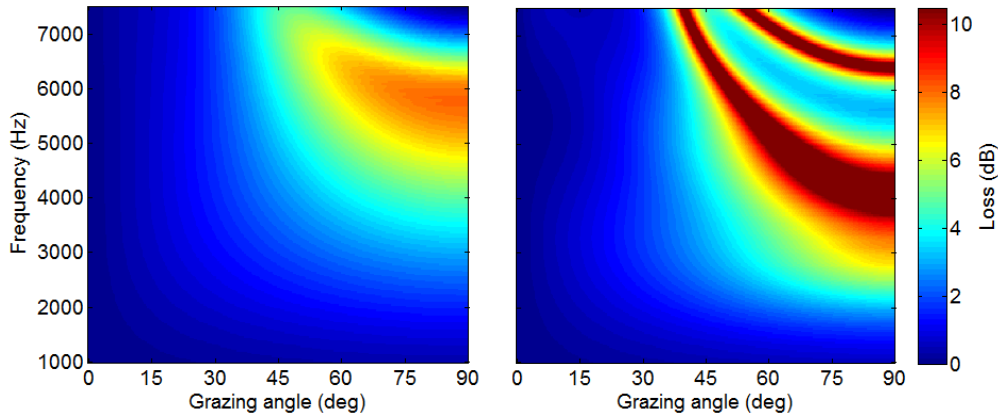
Figure 13: Reflection loss derived from ambient noise by doubling the physical aperture of the array (left), and by synthetically extending the aperture by a factor of two (right).

Figure 14: Magnitude of the first row of the cross spectral density matrix at 2020Hz (top), 4518Hz (center) and 5996Hz (bottom) for a conventional beamformer (CBF) with 32 and 10 physical sensors, and for a synthetic-array processor (SAP) with 5 physical sensors, extended to 10 sensors.

6

Adaptive beamforming for reflection loss estimates

Experience in the past using longer vertical arrays has shown that in certain cases the adaptive beamformer can be applied to estimate reflection loss from ambient noise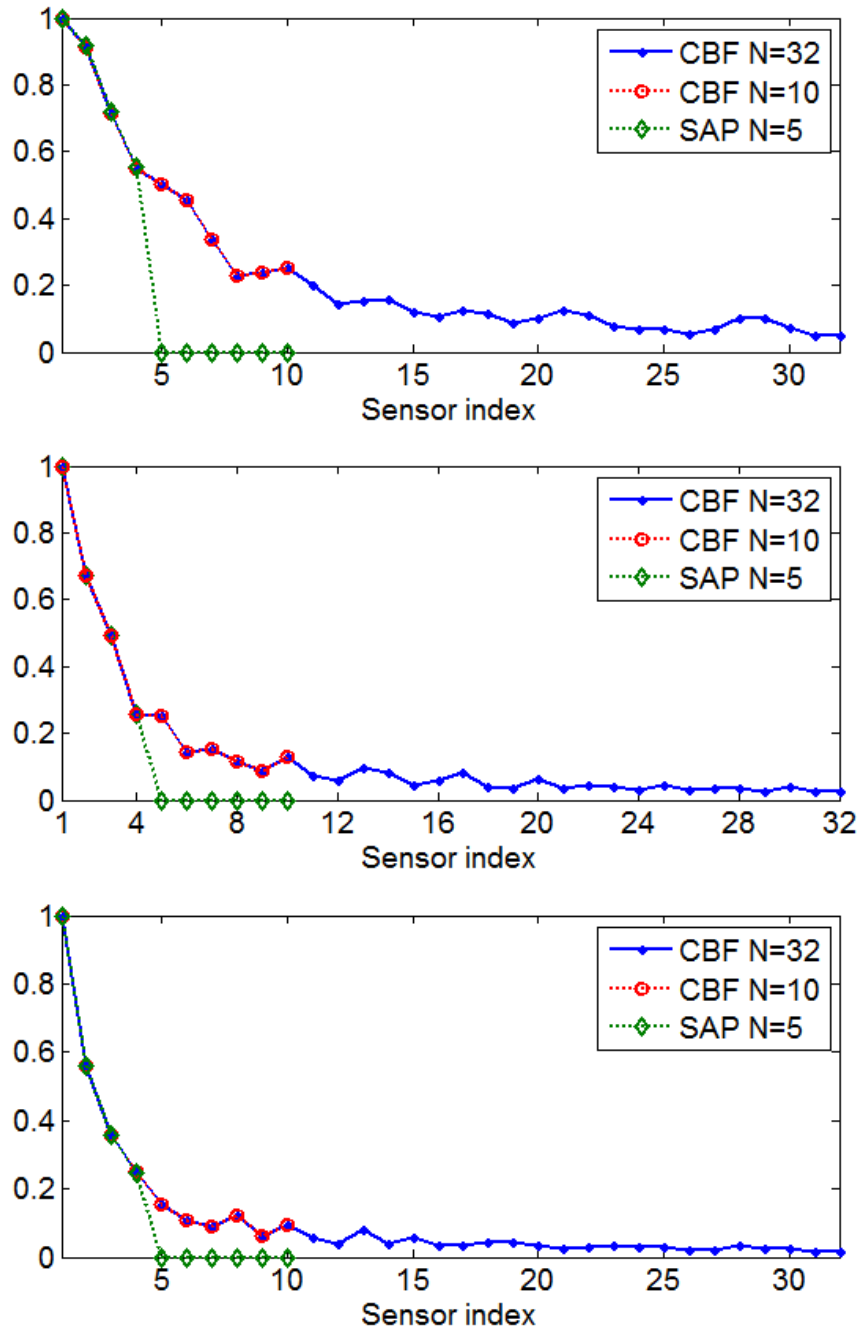 instead of the conventional plane wave beamformer applied in this report. The adaptive beamformer provides, in general, narrower beams in the steering direction and suppresses strong interfering sound sources in directions other than the steering direction. Increased beam resolution in estimating the reflection loss might be achieved by applying the adaptive beamformer to the short GLASS array data. Attempts have been made to gain resolution by applying the adaptive beamformer to synthetic data simulating the GLASS experiments, but no success has been achieved at present. One of the issues with the adaptive beamformer is that the beamwidth in the steering direction is unknown. For estimating the reflection loss, it is essential that the width of the up- and down-looking beams are the same, and this is not necessarily the case for the adaptive beamformer. Further, the adaptive beamformer requires inversion of the cross-spectral density matrix, which can be ill-conditioned, and the number of degrees of freedom is very limited with a 5-element vertical array for the beamformer to perform optimally.

7
Conclusion

The feasibility of characterizing the seabed in terms of reflectivity and stratification using a compact five-element line and tetrahedral (four hydrophones) array has been demonstrated. The array was mounted on a hybrid autonomous underwater vehicle bottom moored at three different locations during the GLASS'12 and GLASS'13 experiments. During GLASS'13 the vehicle was tethered resulting in a vehicle roll and pitch of $3°$ and $8°$, respectively. An ambient noise model was used to simulate the experiment and the numerical results indicate that an array tilt up to $10°$ from vertical has little impact on the reflection loss derived from ambient noise.

The same noise model was applied to underwater scenarios with different classes of bottom types. The calculations of the reflection loss using the compact array indicate that the critical angle and lower cut-off frequency increase as the bottom changes from a soft (low sound speed) to a harder bottom type (high sound speed). The reason for the increase in the lower cut-off frequency for harder bottom types is at present unknown. However, reflection loss modeling from ambient noise received on a compact array clearly shows sensitivity to the bottom type even though it is not equivalent to the plane wave reflection loss. The noise derived reflection loss appears to converge towards the plane wave reflection loss if the length of the array is increased (with hydrophone spacing remaining constant). Therefore, more reliable results can be obtained as the array length increases.

The bottom-type dependence of the noise derived reflection loss observed in the numerical modeling is also observed in the experimental data. Two sites visited in the Mediterranean Sea (GLASS'12) show similar ambient noise reflection loss corresponding to a silt-sand type bottom. This is partly confirmed by previous activities in this area and core data analysis. The data analysis from the experiment in the Gulf of Mexico (GLASS'13) reveals a harder sand-type bottom similar to results obtained from independent experiments.

Geoacoustic properties were estimated at the GLASS'12 and GLASS'13 sites assuming the bottom was an infinite halfspace by an exhaustive sweep through bottom sound speed, density and attenuation values. The combination of bottom properties resulting in the best match between model and data for each site defines the best representation of the bottom properties. In general, lower sound speed and higher attenuation values are determined in the Mediterranean Sea than in the Gulf of Mexico.

Bottom stratification was successfully measured by sea surface generated ambient noise using both the line and tetrahedral arrays in the Mediterranean Sea. There are similarities between this result and bottom-layering measurements by a commercial sub-bottom profiler. However, the seabed appears inhomogeneous in both sets of observations making a direct comparison difficult. Only the bathymetry was detected by ambient noise in the Gulf of Mexico using the line array. Poor results were obtained using the tetrahedral array and was most likely caused by strong interfering sound sources at shallow grazing angles.

There are clear shortfalls in using compact arrays to infer seabed properties based on sea surface generated ambient noise measurements. The methodology is sensitive to strong interfering sound sources which contaminate the up-down beam power ratios obtained by conventional beamforming and resulting in unreliable reflection loss estimates. This is less critical for the sub-bottom profiling as adaptive beamforming is applied to suppress strong interferer from other directions than vertical.

The small aperture of the compact arrays also limits the angular resolution of the measured reflection loss preventing the detection of seabed layering structure from these measurements. The seabed appears as an infinite halfspace from all the reflection loss measurements presented in this report even though independent measurements indicate a layered seabed structure. This is in particular evident at the experimental sites where bottom layers are detected by ambient noise sub-bottom profiling but the noise derived reflection loss appears without fringes. This indicates poor spatial resolution of the ambient noise processing for seabed reflection properties. However, these reflection loss estimates still have seabed information contents as demonstrated in this report, which provide valuable insight into the seabed composition compared to unknown seabed parameters or poor bottom databases.

Despite this shortfall great potential is envisioned in combining autonomous vehicles, compact arrays and utilization of natural-made sound sources for seabed characterization. Smart design and signal processing may circumvent some of the drawbacks noted in this report.

8
Invention

In the context of the ONR-G grant, CMRE declares that no invention has been made during the project. No further reporting regarding this item.

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Publications and presentations

In order to address the publications and acknowledgment of support to ONR-G grant, the following publications and presentations were performed during the execution of the project.

9.1 Publications

- Peter L. Nielsen, Lanfranco Muzi, Martin Siderius and James H. Miller, "GLider Acoustics Sensing of Sediments (GLASS): Experiments and data analysis", NATO STO-CMRE, CMRE-FR-2013-xxx (this report), 2013.

- Peter L. Nielsen, James H. Miller, Martin Siderius, Steven Crocker and Jennifer Giard, "Seabed characterization using ambient noise and compact arrays on an autonomous underwater vehicle", Proceedings of meetings on acoustics, Palais des Congress de Montreal, Montreal, Canada, 2-7 June, POMA 19, Ref. 070030, 2013.

- John Gebbie, Martin Siderius, Peter L. Nielsen, Steven Crocker and Jennifer Giard, "Small boat localization using adaptive three-dimensional beamforming on a tetrahedral and vertical line array", Proceedings of meetings on acoustics, Palais des Congress de Montreal, Montreal, Canada, 2-7 June, POMA 19, Ref. 070072, 2013.

- Peter L. Nielsen, James H. Miller, Martin Siderius, Steven Crocker and Jennifer Giard, "GLASS'12– The glider acoustics sensing of sediments experiment 2012", NATO STO-CMRE, CMRE-FR-2012-007, 2012.

9.2 Presentations

- Martin Siderius, Peter L. Nielsen and James H. Miller, "Extracting seabed properties using ocean noise measured on an autonomous underwater vehicle mounted array", *J. Acoust. Soc. Am.* **134**, 4149, 2013.

- John Gebbie, Martin Siderius, Peter L. Nielsen, Steven Crocker and Jennifer Giard, "Small boat localization using adaptive three-dimensional beamforming on a tetrahedral and vertical line array", *J. Acoust. Soc. Am.* **133**, 3527, 2013.

- Peter L. Nielsen, James H. Miller, Martin Siderius, Steven Crocker and Jennifer Giard, "Seabed characterization using ambient noise and compact arrays on an autonomous underwater vehicle", *J. Acoust. Soc. Am.* **133**, 3395, 2013.

- Peter L. Nielsen, Martin Siderius, Lanfranco Muzi, John Gebbie, Steven Crocker, James H. Miller and Jennifer Giard, "Seabed characterization using ambient noise and compact arrays on an autonomous underwater vehicle (GLASS–GLider Acoustics

Sensing of Sediments)", Visit by ACT and ACO, NATO STO-CMRE, 20-22 August, 2013.

- Peter L. Nielsen, Lanfranco Muzi, Martin Siderius and James H. Miller, "Seabed characterization with underwater glider platforms: Results from GLASS", First CMRE workshop on military applications of underwater glider technology, NATO STO-CMRE, 8-10 October, (summarized in the NATO STO-CMRE report CMRE-MR-2013-013 by Alberto Alvarez) 2013.

10
Recommendations

- Further development and application of more sophisticated array processing algorithms to increase certainty and resolution of the derived seabed properties. This has partly been investigated under the CMRE Visiting Research Program by Mr. Lanfranco Muzi (six weeks effort in 2013). Portions of his results are shown in this report.

- Modify the eFOLAGA control software to eliminate inconvenient behaviors during certain missions such as homing to deployment position if no instructions are provided to the vehicle. This may require involvement of GraalTech S.r.l. as CMRE does not have full access to the control unit software.

- Allocate additional time for Engineering Department (ED) personnel to gain experience in using the eFOLAGA with the newly developed closed-loop-feedback algorithm to automatically balance the vehicle at specific depth.

- Extend the localization capability of the eFOLAGA after ending a mission. This will significantly reduce the risk of losing the vehicle. ED has improved the localization capabilities after the GLASS'13 trial.

- Exercise the system in locations with different bottom properties including areas with known seabed characteristics such as North and South of the Elba Island. Challenges are to detect layering structure in the measured reflection loss that will be consistent with the complementary sub-bottom profiling. An attempt to deploy a compact array on different types of seabeds will be performed during the REP14-MED experiment planned in June 2014.

- Eventually, equip a SLOCUM glider with a longer (approximately 2 m) line array. This will require specific mounting on the glider and employing the hovering capability of the vehicle. Part of this activity may be investigated during the REP14-MED experiment planned in June 2014.

- Verify the approach for interpolating the cross spectral density matrix obtained from a long sparse array. This allows the utilization of a long array with few or limited number of hydrophones.

- Conduct controlled experiments with a proto-type AUV array together with a dense and long array moored at the same location. This will provide ground truth and verify the applicability of the interpolation and extrapolation techniques mentioned above. This activity will be addressed during the REP14-MED experiment planned in June 2014.

- Establish ground truth consisting of coring, independent sub-bottom profiling, other means of acoustic remote sensing of the seabed parameters for comparison and to establish credibility of derived seabed properties from natural-made ambient noise measurements.

- Conduct an ambient noise reflection loss and sub-bottom profiling survey between a deployed sound source and vertical line array. Assess added value by utilizing the ambient noise derived seabed properties in long-range sound propagation predictions for comparison with measured sound propagation.

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Title

GLider Acoustics Sensing of Sediments (GLASS): Experiments and data analysis.

Abstract

Seabed characteristics (geoacoustic properties and scattering strength) are critical parameters for sonar performance predictions. However, this bottom information is considered very difficult and expensive to achieve in the scientific community. In this report, an efficient method for inferring the seabed properties is presented; it relies on a previous methodology using long moored or drifting hydrophone arrays. Results from the GLASS'12 and GLASS'13 sea trials demonstrate the feasibility of using the technique by deploying a hybrid autonomous underwater vehicle hosting a unique hydrophone array consisting of a five-element vertical line array and a four-element tetrahedral array. Seabed reflection and layering properties are estimated from sea surface generated ambient noise acquired during the two trials in different shallow water areas. Results from numerical modeling, data analysis and experimental measurements are presented with emphasis on comparing the seabed characterization at different locations with different bottom properties. Utilization of distant shipping was only demonstrated for the GLASS'12 trial data. The results obtained from both experiments demonstrate the potential of using autonomous underwater vehicles for seabed characterization and surface vessel tracking.

Keywords

Seabed characterization, ambient noise, compact hydrophone array, autonomous underwater vehicles.

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